



ARTICLE

A population pharmacokinetics analysis assessing the exposure of raltegravir once-daily 1200 mg in pregnant women living with HIV

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Abstract

Once-daily two 600 mg tablets (1200 mg q.d.) raltegravir offers an easier treatment option compared to the twice-daily regimen of one 400 mg tablet. No pharmacokinetic, efficacy, or safety data of the 1200 mg q.d. regimen have been reported in pregnant women to date as it is challenging to collect these clinical data. This study aimed to develop a population pharmacokinetic (PopPK) model to predict the pharmacokinetic profile of raltegravir 1200 mg q.d. in pregnant women and to discuss the expected pharmacodynamic properties of raltegravir 1200 mg q.d. during pregnancy based on previously reported concentration-effect relationships. Data from 11 pharmacokinetic studies were pooled ($n = 221$). A two-compartment model with first-order elimination and absorption through three sequential transit compartments best described the data. We assessed that the bio-availability of the 600 mg tablets was 21% higher as the 400 mg tablets, and the bio-availability in pregnant women was 49% lower. Monte-Carlo simulations were performed to predict the pharmacokinetic profile of 1200 mg q.d. in pregnant and nonpregnant women. The primary criteria for efficacy were that the lower bound of the 90% confidence interval (CI) of the concentration before next dose administration (C_{trough}) geometric mean ratio (GMR) of simulated pregnant/nonpregnant women had to be greater than 0.75. The simulated raltegravir C_{trough} GMR (90% CI) was 0.51 (0.41–0.63), hence not meeting the primary target for efficacy. Clinical data from two pregnant women using 1200 mg q.d. raltegravir showed a similar C_{trough} ratio pregnant/nonpregnant. Our pharmacokinetic results support the current recommendation of not using the raltegravir 1200 mg q.d. regimen during pregnancy until more data on the exposure-response relationship becomes available.

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INTRODUCTION

Antiretroviral treatment is particularly important in pregnant women living with HIV, because adequate antiretroviral drug (ARV) therapy dramatically reduces the risk of mother-to-child transmission of HIV.^{1,2} However, physiological changes during pregnancy often decrease the ARV exposure, as a result of hampered absorption, increased volume of distribution and/or increased metabolism and elimination.^{3,4} To ensure adequate ARV efficacy and safety, the pharmacokinetics of every ARV has to be examined in pregnant women living with HIV. Generally, it takes around 6 years to fill this knowledge gap after drug registration, during which pregnant women and their unborn babies are at risk for inadequate antiretroviral therapy.⁵

In 2017, a novel raltegravir formulation was granted market authorization. This once-daily (q.d.) regimen of two 600 mg tablets (1200 mg q.d.) offers an easier treatment option compared with the twice-daily (b.i.d.) regimen of one 400 mg tablet (400 mg b.i.d.). The raltegravir 1200 mg q.d. regimen demonstrated non-inferior efficacy and similar safety to the 400 mg b.i.d. regimen at 96 weeks.^{6,7} The 600 mg formulation can be dosed once-daily because of the less erratic absorption, higher bioavailability, higher loading dose and decreased influence of concomitant food intake.⁸ When dosed as 1200 mg q.d. the mean raltegravir C_{trough} is 38% lower compared with dosing as 400 mg b.i.d., making this regimen theoretically more sensitive for possible concentration lowering influences, such as drug-drug interaction and pregnancy.⁸ No clinical pharmacokinetic, efficacy, or safety data of the 600 mg formulation in pregnant women exists up to date, and therefore this formulation is not recommended to be used during pregnancy.

The raltegravir 400 mg b.i.d. regimen is among the preferred regimens for pregnant women in high-income settings, as it produces rapid viral load decline, has low potential for drug-drug interactions and the experience with its use in pregnancy is growing.^{1,9} Pharmacokinetic data showed that the raltegravir exposure decreases on average by 29%–54% in pregnant women treated with raltegravir 400 mg b.i.d.^{10,11} The sufficient rate of virologic response, large pharmacokinetic variability, and debatable concentration-efficacy relationship led to the conclusion that the decreased exposure of the b.i.d.-regimen during pregnancy would not be of clinical relevance.^{10,11}

The concentration-efficacy relationship is debatable for raltegravir; no relationship could be observed for the 400 mg b.i.d. and 1200 mg q.d. regimen up to date.¹² However, a relationship has been observed for the raltegravir 800 mg q.d. regimen. This regimen demonstrated inferiority in achieving HIV RNA < 50 copies/ml compared with the 400 mg b.i.d. regimen.¹³ Logistic regression models and a receiver operating characteristic (ROC) curve showed that individuals

Study Highlights

WHAT IS THE CURRENT KNOWLEDGE ON THE TOPIC?

The twice-daily regimen of one 400 mg raltegravir tablet is among the preferred regimens for pregnant women and adequate clinical, pharmacokinetic, and safety data is available. However, such data do not exist for the once-daily regimen of two 600 mg raltegravir tablets.

WHAT QUESTION DID THIS STUDY ADDRESS?

Is the 1200 mg once-daily raltegravir regimen an effective treatment option during pregnancy based on the estimated pharmacokinetic profile and the expected pharmacodynamic properties of this regimen?

WHAT DOES THIS STUDY ADD TO OUR KNOWLEDGE?

Simulations with the developed population pharmacokinetic (PopPK) model suggested inadequate raltegravir exposure in third trimester women using raltegravir 1200 mg q.d.

HOW MIGHT THIS CHANGE DRUG DISCOVERY, DEVELOPMENT, AND/OR THERAPEUTICS?

This PopPK model serves as an *in silico* prediction tool to predict raltegravir exposure in various populations using the 400 mg and 600 mg tablet formulations. Predictions showed restraining the once-daily raltegravir regimen in pregnant women seems reasonable until more data become available.

with a $C_{trough} < 0.020$ mg/L had a greater chance of failing to achieve viral suppression, although the sensitivity was low (45%) and the specificity moderate (75%).¹² The mean C_{trough} of patients treated with raltegravir 800 mg q.d. (0.018 mg/L) was lower as the observed mean C_{trough} of pregnant patients treated with 400 mg b.i.d. (0.064 and 0.077 mg/L), indicating efficacy of this regimen during pregnancy.^{10,11,13} This also suggests no concentration-effect relationship could be observed for the 400 mg b.i.d. because the pharmacokinetic parameters remain above the minimum concentration needed for efficacy.¹²

The availability of multiple proven effective and safe alternative ARVs makes it challenging, or even impossible, to timely collect clinical pharmacokinetic data of the raltegravir 1200 mg q.d. regimen in pregnant women. As the formulation, dosage, and dosing schedule differ for the 1200 mg q.d., we cannot directly apply the findings from the pharmacokinetic studies in pregnant women treated

with 400 mg b.i.d. raltegravir. A population pharmacokinetic (PopPK) model can be used to characterize the concentration-time course of a drug for individual subjects, and to simulate concentration-time profiles under varying conditions as different dosing regimens and populations. This approach enables a timely assessment of the applicability a new formulation in pregnant women without putting a variety of women at risk. This study aims to (a) develop a PopPK model for raltegravir in individuals with and without HIV-infection (400 mg and 600 mg formulations), including pregnant women (400 mg formulation), (b) to predict the pharmacokinetic profile of raltegravir 1200 mg q.d. in pregnant women, and (c) to discuss the expected pharmacodynamic characteristic of raltegravir 1200 mg q.d. in pregnancy based on the published concentration-effect relationship.

METHODS

Pharmacokinetic data

Data from 11 pharmacokinetic studies with raltegravir and rich sampling schedules were pooled.^{8,10,14–21} These studies include a combination of healthy and HIV-infected subjects taking 400 mg and 600 mg raltegravir tablets, and pregnant subjects taking the 400 mg tablets. The study protocols and subject characteristics are summarized in Table 1, and detailed information can be found in the original publications.^{8,10,14–21} Twenty-two European, HIV-infected, pregnant women treated with a 400 mg b.i.d. raltegravir-based regimen were included to determine the effect of pregnancy on the pharmacokinetics of raltegravir.¹⁰ These women underwent intensive pharmacokinetic sampling during the third trimester (preferably at 33 weeks gestation) and postpartum (4–6 weeks after giving birth). The exclusion criteria are described in the Supporting Information.

Development population pharmacokinetic model

A PopPK model was developed using NONMEM 7.4 (ICON Development Solutions, Hanover, MD, USA). The first-order conditional estimation method with eta-epsilon interaction was used. Pirana 2.9.7 (Certara, Princeton, NJ, USA) was used as an interface to NONMEM and to structure and document model development, R 3.5.3 (R Foundation for Statistical Computing, Vienna, Austria) for data management, graphical visualization, and evaluation, and Perl speaks NONMEM (PsN) for automation of a diverse range of processes related to model development.²²

Several PopPK models have previously been developed for healthy or HIV-infected children and adults treated with raltegravir 400 mg tablets.^{23–26} However, visual predictive checks (VPCs) showed none of these models was able to directly describe the absorption and elimination profile adequately in our larger dataset. Model development was conducted in a step-wise fashion.²⁷ We started with the pharmacokinetic data of healthy subjects using raltegravir 1200 mg q.d., because this regimen has a less variable absorption and a longer dosing interval, facilitating estimation of the primary pharmacokinetic parameters. Subsequently, the data of healthy subjects using raltegravir 400 mg b.i.d., patients living with HIV using raltegravir 1200 mg q.d., patients living with HIV using raltegravir 400 mg b.i.d., and pregnant women living with HIV using raltegravir 400 mg b.i.d. were added step-wise. The model structure was re-evaluated after each round, including new data.

One, two, and three compartment models were evaluated. First- and zero-order (dual) absorption models, entero-hepatic recirculation, mixture, and transit absorption models were evaluated to describe the variable absorption of raltegravir. Model selection was based on maximum likelihood statistics (quantified by the objective function value [OFV]), with a 5% significance level (dOFV 3.84), physiological plausibility, precision in parameters estimates, standard goodness-of-fits plots, and VPCs.

The typical bioavailability (F) value was set to 1, because no intravenous data were available to allow for estimation of the absolute bioavailability. For the stochastic component of the model, log-normal and box-cox transformed distributions for the interindividual variability (IIV) and interoccasion variability (IOV) between doses were tested.^{28,29} Normally distributed additive, proportional, and combined residual error model structures were tested, next to a dynamic transform-both-sides approach, which allows estimation of both the shape and scedasticity parameters.²⁹ In addition, a time-varying approach to empirically account for model errors resulting from the erratic and highly variable absorption of raltegravir was tested with a different proportional error for the time before and after 3 h (the average timepoint for maximum concentration [C_{max}]).^{2,30} The lower limit of quantification (LLOQ) of the different studies are shown in Table 1. Below the limit of quantification (BLOQ) values were included as LLOQ divided by 2 (1% of the total samples). The consecutive BLOQ values in the elimination phase and the predose BLOQ samples of single-dose studies were excluded (2% of the total samples).

All flow and volume parameters were scaled with body weight according allometric theory, with fixed allometric exponents of 0.75 for flow parameters and 1 for volumes of distribution.³¹ For pregnant women, postpartum weight was used because applicability of allometric scaling for pregnant women has not been established and could confound the

TABLE 1 Patient and study characteristics summarized by study

Reference	Number of patients	Number of samples	Number of patients included	Number of samples included	Population	Female sex, %	Age, years [median (range)]	Weight, kg [median (range)]	Raltegravir Regimen	Fed status at drug intake	Sampling design, hours postdose	Lower limit of quantification, mg/L
14	24	564	24	515	Healthy	54%	31 (18–55)	67 (48–99)	400 mg b.i.d.	Fasted	0, 0.5, 1, 1.5, 2, 3, 4, 5, 6, 8, 10, 12 at steady state	0.014
15	18	432	16	176	Healthy	50%	43 (22–55)	71 (52–93)	400 mg b.i.d.	Fasted	0, 0.5, 1, 1.5, 2, 3, 4, 5, 6, 8, 10, 12 after single dose	0.014
16	24	528	23	228	Healthy	52%	35 (20–53)	70 (49–103)	400 mg b.i.d.	Fasted	0, 0.5, 1, 1.5, 2, 3, 4, 6, 8, 10, 12 at steady state	0.014
17	24	528	22	379	Healthy	53%	47 (18–53)	74 (59–95)	400 mg b.i.d.	Fasted	0, 0.5, 1, 1.5, 2, 3, 4, 6, 8, 10, 12 at steady state	0.014
18	18	393	18	321	HIV-infected	17%	45 (37–75)	76 (67–110)	400 mg b.i.d. + 800 mg q.d.	Moderate fat ^a	0, 0.5, 1, 1.5, 2, 3, 4, 6, 8, 12/24 at steady state	0.014
10	22	353	22	313	HIV-infected, pregnant	100%	33 (23–44)	65 (43–89)	400 mg b.i.d.	Moderate fat ^a	0, 0.5, 1, 2, 3, 4, 6, 8, 12 at steady state	0.014
8	18	594	18	561	Healthy	89%	41 (25–55)	64 (49–97)	1200 mg q.d.	Fasted + Low-fat + high-fat ^a	0, 0.5, 1, 2, 3, 4, 6, 8, 12, 24, 48 after single dose	0.002
8	23	532	23	460	Healthy	30%	42 (25–55)	77 (60–96)	1200 mg q.d.	Fasted	0, 0.5, 1, 2, 3, 4, 6, 8, 12, 24 at steady state	0.002
19	21	560	21	507	Healthy	10%	32 (21–52)	83 (59–111)	1200 mg q.d.	Fasted	0, 0.5, 1, 2, 3, 4, 6, 8, 12, 24, 48, 72, 167.5 after single dose	0.002
20	14	364	14	336	Healthy	64%	40 (21–55)	72 (59–95)	1200 mg q.d.	Moderate fat ^a	0, 0.5, 1, 1.5, 2, 3, 4, 6, 8, 12, 16, 48, 72, 263 after single dose	0.002
21	20	924	20	220	HIV-infected	10%	53 (29–62)	75 (54–108)	1200 mg q.d.	Fasted	0, 0.5, 1, 1.5, 2, 3, 4, 6, 8, 12, 16, 24 at steady-state	0.002

^aLowfat: 389 kcal, 6.9% fat; moderate-fat: 650–844 kcal, 48% fat; high-fat: 997 kcal, 51% fat.

potential pregnancy effect.³¹ In the case of missing postpartum weight ($n = 4$), the weight was calculated from the third trimester weight times the mean difference between third trimester and postpartum weight (-7%).

Covariate testing was based on physiological plausibility and results from previous population pharmacokinetic models. Sex was tested as covariate on F, and White ethnicity as covariate on central volume of distribution (V_c).²⁴ We tested atazanavir and efavirenz co-administration as covariates on F and CL.^{19,20,32} Pregnancy was tested as a dichotomous covariate on CL, mean absorption time (MAT), F, V_c , and absorption rate (K_a).³ Covariate-parameter relations were evaluated using a forward inclusion and backward elimination approach. The selection was based on biological plausibility, previous models, and maximum likelihood statistics (quantified by a 5% significance level [dOFV 3.84]) applied for likelihood ratio testing of nested models. Because the pregnancy covariate was the most defining covariate, this covariate was evaluated extensively. A sensitivity analysis was performed for all significant covariate effects of pregnancy separately. This means that separate simulations were carried out and that we evaluated whether the choice for a covariate pregnancy defined the conclusion based on our primary end point.

Different meal types have considerable and variable effect on the pharmacokinetic profile of raltegravir.^{8,33} A low-fat meal compared with fasted conditions decreases raltegravir exposure for the 400 mg and 600 mg tablets in a similar matter.⁸ The pharmacokinetic profile of raltegravir is not meaningfully altered by a moderate-fat meal, whereas the exposure is increased with a high-fat meal and this effect is more pronounced for the 400 mg formulation than the 600 mg formulation.^{8,33} Only data of the 600 mg formulation across different meal types was available to us. The effect of food (irrespective of meal type), a low-fat meal (389 kcal, 6.9% fat) and a moderate-fat meal (650–844 kcal, 48% fat) as a covariate on F and MAT in subjects using the 600 mg formulation was tested, assuming a similar food effect for the 400 mg formulation. The studies examining the 400 mg raltegravir formulation were performed under fasted or moderate fat conditions, as shown in Table 1.

Simulations

To predict the pharmacokinetic profile of raltegravir 1200 mg q.d. in pregnant and nonpregnant individuals, simulations with the final model were performed. Monte-Carlo simulations with 3000 individuals with multilevels of random effect (parameter uncertainty, IOV, and IIV) were conducted. The procedure was repeated 1000 times using Stochastic Simulation and Estimation (SSE) from PsN to account for parameter uncertainty. The parameter uncertainty was obtained from a sampling importance resampling

(SIR) procedure.³⁴ The covariate distribution in the simulation dataset was derived from 186 pregnant and postpartum women of the European Pharmacokinetics of newly developed ANtiretroviral agents in HIV-infected pregnant women (PANNA) study (www.pannastudy.com). These covariates were resampled, maintaining the covariate structure, 3000 times with 10% noise. Simulations were conducted without residual error.

Six scenarios were evaluated: the concentration-time curve of pregnant and nonpregnant women treated with raltegravir 1200 mg q.d. at steady-state under fasted, low-fat, and moderate-fat conditions. High-fat conditions were not simulated because the model did not perform sufficiently under these conditions and it was not believed to be a commonly occurring meal type (~ 1000 kcal and 50% fat). We assumed that postpartum weight was similar to nonpregnant weight. The same 3000 individuals were simulated under the six different conditions. The AUC_{0-24h} was derived from the model and the C_{trough} was defined as the individual predicted concentration on 24 h after drug intake.

Target values simulation

As a proxy for efficacy, the C_{trough} of pregnant women on the 1200 mg q.d. raltegravir dosing regimen was compared with the same metric in nonpregnant women. The lower bound of the 90% confidence interval (CI) of the GMR C_{trough} of pregnant / nonpregnant women was defined to be greater than 0.75, similarly to the target established in drug-drug interaction studies with the raltegravir 1200 mg regimen by the manufacturer and regulatory authorities.^{21,35} A secondary outcome parameter was the proportion of individuals with a C_{trough} less than 0.020 mg/L among pregnant compared with nonpregnant women using 1200 mg q.d. This target was derived from the ROC curve from the pharmacokinetic data of the inferior 800 mg q.d. regimen (converted from 45 nM by calculating with a raltegravir molar mass of 0.0004444 mg/nmol).¹²

Additionally, the simulated GMRs were compared with the clinical data of two women included in the PANNA study. This European, open-label, multicenter, within-patient, pharmacokinetic Phase 4 study includes pregnant women living with HIV using raltegravir 1200 mg q.d. At third trimester (~ 33 weeks) and postpartum (preferably 4–6 weeks), EDTA blood samples were collected at 0, 0.5, 1, 2, 3, 4, 6, 8, 12, and 24 h after observed intake of raltegravir with moderate-fat food (650 kcal; 30 g fat). Plasma concentrations were centrally analyzed using a validated liquid chromatography-based assay (LLOQ 0.01 mg/L).³⁶ Pharmacokinetic parameters were determined using non-compartmental analysis (Phoenix 64 version 8.1; Certara). The detailed protocol of this study has been described in an earlier publication.¹⁰

RESULTS

Data from 11 studies with 226 individuals and 5772 sampling points were pooled. In the following order, we excluded 1164 samples due to interacting comedication, 99 BLOQ values (while 70 were imputed as LLOQ/2) and 493 nonevaluable samples, as defined in the Methods section. Ultimately, the PopPK model was built with 221 individuals and 4016 sampling points, as shown in Table 1.

A two-compartment model with first-order elimination and absorption through three sequential absorption compartments best described the data. The structure of the model is depicted in Figure 1. The transit rate constant (k_{tr}) was estimated and MAT was based on Equation 1:

$$k_{tr} = n + 1 / MAT(1)$$

with n equals the number of transit compartments. We included log-normally distributed IIV on CL, V_c , Q , V_p , and the residual error, as well as log-normally distributed IOV between doses on F and MAT. IIV correlations on CL with Q , and Q with V_p were included (dOFV -62.5). A time-varying and log-normally distributed proportional error structure with one proportional error for first 3 h after drug intake and one for more than 3 h after drug intake was included to empirically account for the

larger observed variability during the absorption phase compared with the disposition phase (dOFV -112.7).²

The following covariate-parameter relationships were included: a dichotomous covariate for intake with food (irrespective of meal type) on MAT (dOFV -46.76 , 160% increase with food), a dichotomous covariate for atazanavir co-administration on CL (dOFV -12.43 , 17% decrease with atazanavir), a dichotomous covariate for the 600 mg formulation on F (dOFV -5.88 , 21% increase with 600 mg formulation vs. 400 mg formulation), a dichotomous covariate for intake with a low-fat meal on F (dOFV -46.98 , 45% decrease with a low-fat meal), a dichotomous covariate for the 600 mg formulation on the magnitude of IOV in F (dOFV -127.31 , 72% decrease with 600 mg formulation vs. 400 mg formulation), a dichotomous covariate for efavirenz co-administration on F (dOFV -5.28 , 17% decrease with efavirenz), and a dichotomous covariate for being pregnant on F (dOFV -17.82 , 49% decrease during pregnancy). The sensitivity analysis for the pregnancy covariate is included in the Supporting Information. The final population estimates are shown in Table 2.

A VPC based on 1000 samples and stratified for pregnancy and tablet formulation, is shown in Figure 2. This VPC indicated an adequate model fit to the observed concentration-time data. Standard goodness-of-fit plots indicated no bias in the structural model or unaccounted data heterogeneity (Supporting Information).

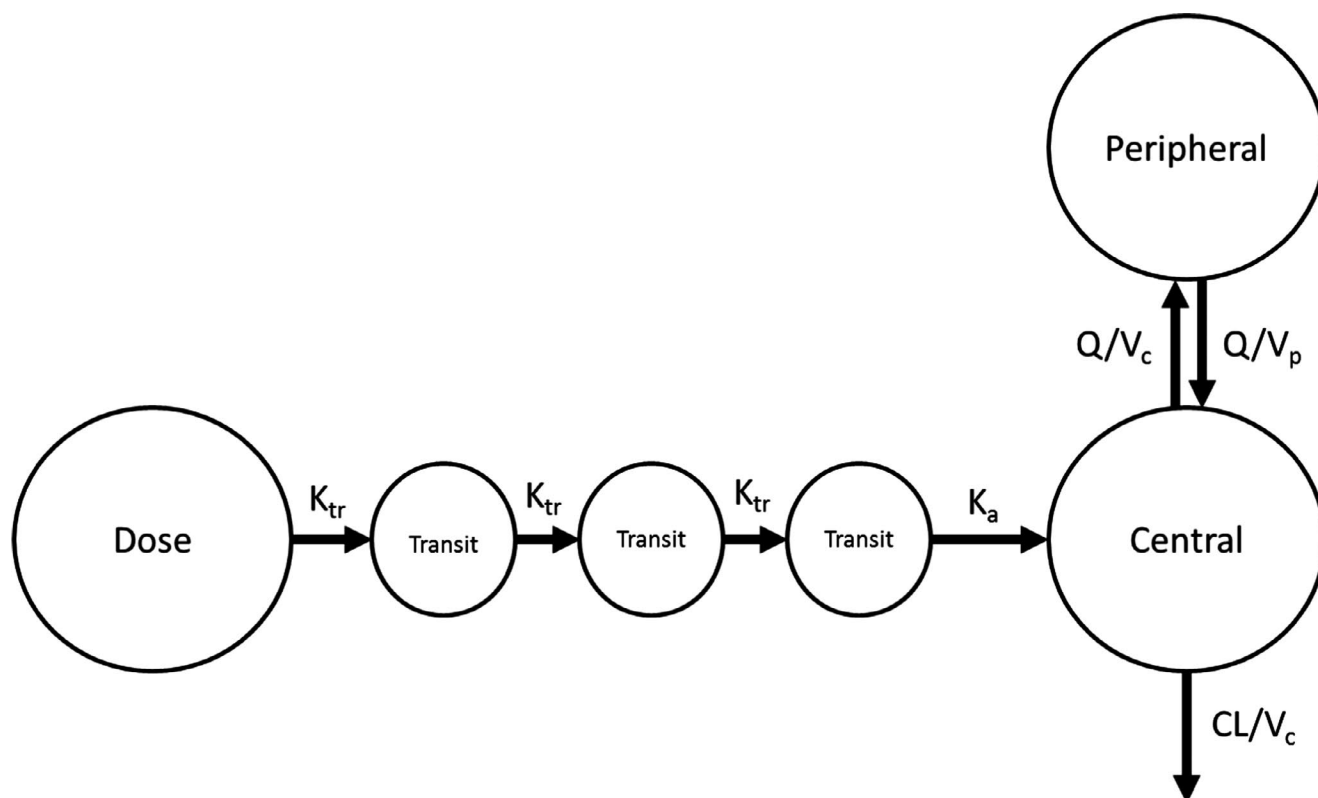


FIGURE 1 Final model structure. CL, clearance; K_{tr} , first-order transit rate; K_a , first-order absorption rate; Q , intercompartmental clearance; V_c , central volume of distribution; V_p , peripheral volume of distribution.

TABLE 2 Final population estimates

Parameter	Parameter estimate	RSE (%) from SIR
K_a , h ⁻¹	0.741	2
MAT, h, fasted	0.336	8
Factor change in MAT fed ^a	1.6	19
V_c/F , L ^b	44.3	7
CL/F, L/h ^b	55.8	5
Factor change in CL with atazanavir ^a	-0.17	25
Q/F, L/h ^b	5.68	7
V_p/F , L ^b	92.8	9
F^c	1 (fixed)	
Factor change in F 600 mg formulation ^a	0.209	26
Factor change in F low-fat meal ^a	-0.459	9
Factor change in F pregnancy ^a	-0.487	14
Factor change in F efavirenz co-administration ^a	-0.167	37
IIV V_c/F , %	69.7 ^d	14 ^e
IIV CL/F, %	28.6 ^d	6 ^e
Correlation coefficient with Q/F	0.18	41
IIV Q/F, %	71.5 ^d	12 ^e
Correlation coefficient with V_p/F	0.59	10
IIV V_p/F , %	115.2 ^d	22 ^e
IIV residual error, %	25.6 ^d	5 ^e
IOV F, %, 400 mg formulation	112.1 ^d	17 ^e
Factor change in IOV in F 600 mg formulation ^f	-0.718	4
IOV MAT (%)	140.5 ^d	21 ^e
Proportional residual error ≤ 3 h after drug intake, %	43.5 ^d	3 ^e
Proportional residual error > 3 h after drug intake, %	29.0 ^d	2 ^e

Abbreviations: CL/F apparent clearance; F, bioavailability; IIV, interindividual variability; IOV, interoccasion variability; K_a , first-order absorption rate; MAT, mean absorption time; Q/F, apparent intercompartmental clearance; RSE, relative standard error; SIR, sampling importance resampling; V_c/F , apparent central volume of distribution; V_p/F , apparent peripheral volume of distribution.

^aThe covariate effects of fed conditions on MAT, atazanavir on CL, 600 mg formulation on F, low-fat meal on F, pregnancy on F, efavirenz on F and 600 mg formulation on IOV F were obtained with: MAT in fed conditions = MAT fasted * (1 + factor change in MAT fed); CL when atazanavir co-administration = clearance * (individual weight / 70)^{0.75} * (1 + factor change in CL with atazanavir); F in pregnancy, 600 mg formulation, low-fat meal and efavirenz co-administration = 1 * (1 + factor change in F 600 mg formulation) * (1 + factor change in F low-fat meal) * (1 + factor change in F pregnancy) * (1 + factor change in F efavirenz-co-administration).

^bFor the typical individual weighing 70 kg.

^cThe reference case for F is non-pregnant, the 400 mg formulation, other food conditions as low-fat, and no efavirenz co-administration.

^dTransformed from log normal variance to %CV with $\sqrt{(\exp(\text{variance})-1)}$.

^eTransformed individual SIR results from log normal variance to %CV with $\sqrt{(\exp(\text{variance})-1)}$ for calculation of the relative standard error.

^fThe covariate effect of 600 mg formulation on the IOV F was obtained with: (1 + factor change in IOV in F 600 mg formulation) * IOV F 400 mg formulation.

A 21% higher bioavailability (relative standard error [RSE] 26%) was estimated for the 600 mg tablets in comparison to the 400 mg tablets, and a 49% lower bioavailability (RSE 14%) was estimated in pregnant compared with nonpregnant women. Predictions of raltegravir AUC_{0-24h} and C_{trough} in pregnant women treated with 1200 mg q.d. raltegravir are shown in Table 3. The predicted geometric mean (GM; 95% CI) raltegravir C_{trough} was 0.024 (0.002–0.133), 0.014 (0.001–0.086), 0.027 (0.003–0.160) mg/L in pregnant women treated with 1200 mg q.d. raltegravir in fasted, low-fat, and moderate-fat conditions, respectively. Simulations of nonpregnant and pregnant women treated with 1200 mg q.d. raltegravir showed that the GMR (90%CI) was 0.51 (0.41–0.63; Table 3). The lower bound of the 90% CI GMR was not greater than 0.75, hence the primary efficacy target was not fulfilled.

The predicted proportion with a C_{trough} less than 0.020 mg/L was substantially higher in pregnant women compared with nonpregnant women using 1200 mg q.d.. Under fasted conditions, 36.5% of the simulated pregnant women had a C_{trough} less than 0.020 mg/L, compared with 17.1% of the simulated nonpregnant women. This was 58.6 versus 31.7%, and 33.7% versus 15.2% for low-fat and moderate-fat conditions, respectively.

These results were similar compared with the clinical data of two pregnant women from the PANNA study, as depicted in Figure 3. Woman number 1 was cotreated with darunavir/ritonavir 800/100 mg q.d. At 33 weeks gestational age, raltegravir AUC_{0-24h} and C_{trough} were 16.25 mg*h/L and 0.012 mg/L, respectively. At 4 weeks postpartum, raltegravir AUC_{0-24h} and C_{trough} were 22.72 mg*h/L and 0.027 mg/L, respectively. This corresponds to a C_{trough} ratio pregnant / nonpregnant of 0.52. The second woman was cotreated with emtricitabine / tenofovir disoproxil fumarate 200 / 245 mg and an AUC_{0-24h} of 13.09 mg*h/L and C_{trough} of less than 0.01 mg/L was estimated at 32 weeks gestational age. At 5 weeks postpartum, we assessed an AUC_{0-24h} of 27.24 mg*h/L and C_{trough} of 0.015 mg/L. Although BLOQ during the third trimester, the C_{trough} was measurable and we calculated an approximate C_{trough} ratio pregnant / nonpregnant of 0.46. Although these women had a C_{trough} less than 0.020 mg/L at the third trimester, both women had an HIV RNA viral load less than 50 copies/mL at the third trimester and at the postpartum visit. Woman number 1 delivered a healthy boy of 4010 gram at 40 weeks gestational age. The boy had a negative HIV viral load at delivery. The healthy boy of woman number 2 was born at 39 weeks of gestational age, was 2886 gram, and also had a negative HIV viral load at delivery.

DISCUSSION

With this PopPK model, we performed a first evaluation of the drug exposure with the 1200 mg q.d. raltegravir regimen in pregnant women. We estimated that physiological changes during the third trimester of pregnancy decrease the

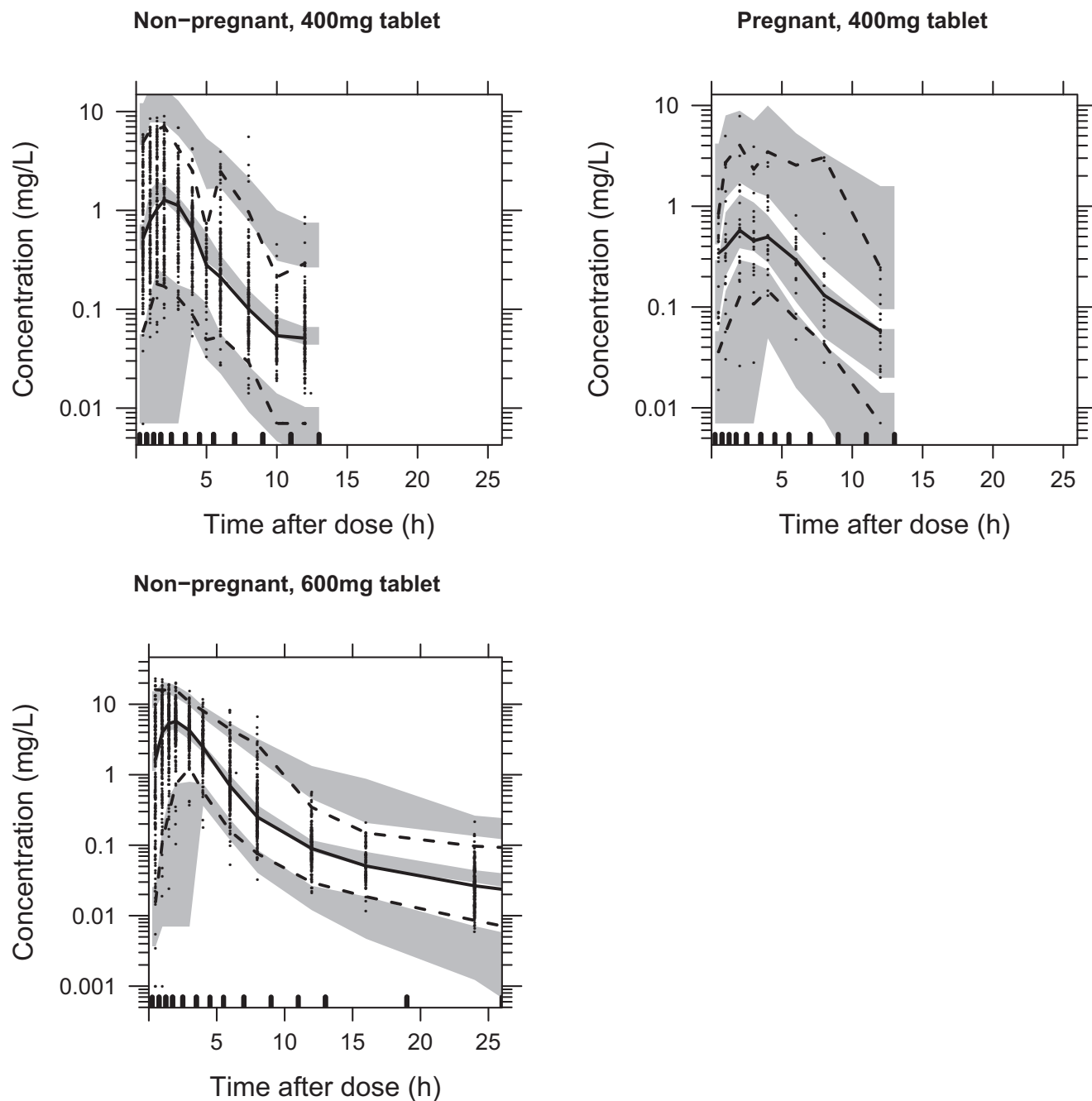


FIGURE 2 Visual predictive check of the final model (simulations $n = 1000$). The observations are indicated by black dots. The median (continuous line) and 2.5th and 97.5th percentiles (dashed lines) of the observations are shown. The gray shaded areas indicate the 95% confidence interval around the median, 2.5th and 97.5th percentile of the simulated data. Vertical markers are sampling points.

bioavailability of raltegravir with 49% compared with non-pregnant women. The predetermined primary target was not met, and simulations predicted that a substantial part of the pregnant women treated with 1200 mg q.d. had an anticipated C_{trough} less than 0.020 mg/L.

The primary target was set on the basis of the criteria of the 1200 mg q.d. regimen used in interaction studies from the manufacturer and the submission to the European regulatory authority.^{21,35} No pharmacokinetic target has been established for the raltegravir 1200 mg q.d. regimen, as no clear

relationship between plasma concentrations and virologic response has been established up until now for this regimen.⁷ Therefore, we believe that a conservative approach is suitable, aiming at a marginal deviation from the general population for which efficacy has been demonstrated. The efficacy of the 1200 mg q.d. regimen was shown in a noninferiority trial in a population of treatment-naïve adults ($n = 797$) with HIV RNA greater than 1000 copies/ml with a median (interquartile range) raltegravir C_{trough} of 0.050 (0.028–0.094) mg/L.⁷

TABLE 3 Simulated pharmacokinetic parameters of pregnant and nonpregnant women treated with 1200 mg q.d. (two tablets of 600 mg)

Condition	Parameter	Simulations repeated 1000 times with alternative parameters estimates (<i>n</i> individuals = 3000)				Simulations with typical parameter estimates (<i>n</i> individuals = 3000)		Historical reference
		Pregnant vs. nonpregnant, GMR (90% CI)	% Pregnant women with C_{trough} <0.020 mg/L, GM (95% CI)	% Nonpregnant women with C_{trough} <0.020 mg/L, GM (95% CI)		Pregnant, GM (95% CI)	Nonpregnant, GM (95% CI)	
Fasted	AUC_{0-24h} , mg \cdot h/L	0.51 (0.41–0.63)	36.5 (25.9–50.2)	17.1 (12.5–22.2)		13.06 (5.69–28.53)	25.45 (11.09–55.60)	26.46 (22.83–30.66) ^{a,b}
	C_{trough} , mg/L					0.024 (0.002–0.133)	0.047 (0.004–0.250)	0.036 (0.027–0.047) ^{a,b}
Low-fat	AUC_{0-24h} , mg \cdot h/L		58.6 (45.2–72.3)	31.7 (24.7–40.2)		7.06 (3.08–15.43)	13.76 (6.00–30.08)	14.62 (12.69–16.85) ^{a,c,d}
	C_{trough} , mg/L					0.014 (0.001–0.086)	0.028 (0.003–0.169)	0.021 (0.016–0.039) ^{a,c}
Mod-fat	AUC_{0-24h} , mg \cdot h/L		33.7 (23.6–47.3)	15.2 (11.0–20.2)		13.06 (5.69–28.53)	25.45 (11.09–55.60)	NA
	C_{trough} , mg/L					0.027 (0.003–0.160)	0.052 (0.005–0.312)	NA

AUC, area under the curve; CI, confidence interval; C_{trough} , concentration before next dose administration; GM, geometric mean; GMR, geometric mean ratio; Mod-fat, moderately fat; NA, not applicable.^aCalculated from nM to mg/L and h \cdot nM to mg \cdot h/L by multiplying with molar mass of raltegravir of 0.0004444 mg/nmol.^bMultiple-dose pharmacokinetic study (*n* = 23) (7).^cSingle-dose pharmacokinetic study (*n* = 16) (7).^d AUC_{0-48h} reported.

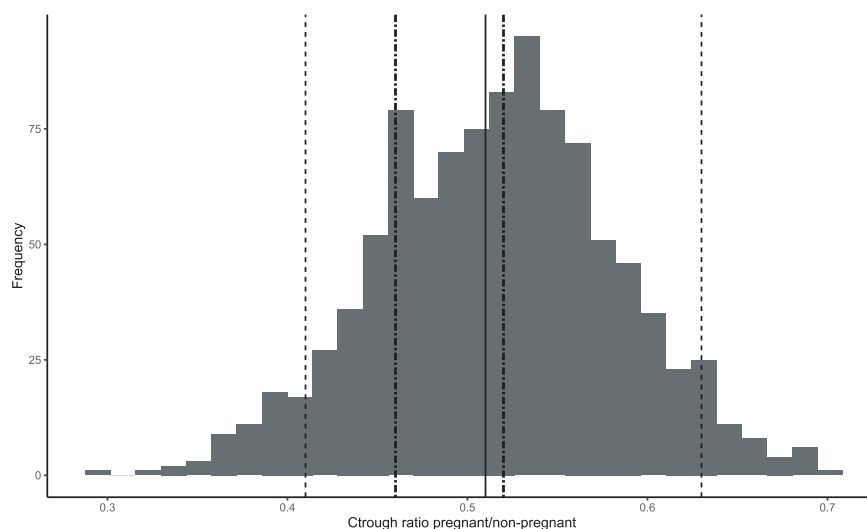


FIGURE 3 Comparison of the simulated GMR pregnant / nonpregnant C_{trough} with the ratio derived from the clinical data of two pregnant women. The median (solid line) and 5th and 95th (dashed line) percentiles of the simulated GMR C_{trough} are shown. The ratio third trimester / postpartum C_{trough} of the two clinical cases are indicated by the dot-dashed line. C_{trough} , concentration before next dose administration; GMR, geometric mean ratio.

We predicted that a substantial proportion of the pregnant women using raltegravir 1200 mg q.d. will have a C_{trough} less than 0.020 mg/L. This C_{trough} target was derived from a study with raltegravir 800 mg q.d. in treatment-naïve patients with a high viral HIV load at baseline, so this target may not be applicable to our population.¹² In addition, the C_{trough} , C_{max} , and AUC relate differently to each other for the 1200 mg q.d. dosing regimen compared with the 400 mg b.i.d. and 800 mg q.d. regimens, and it remains unclear whether this C_{trough} target can be applied to other dosing regimens. Clinical data suggest that the C_{trough} target is not applicable to the 1200 mg q.d. regimen because no direct relationship between a low C_{trough} (median C_{trough} of 0.019 mg/L in the lowest quartile) and virologic failure could be observed in 797 participants during the Phase 3 study with the 1200 mg q.d. regimen.¹³

The current PopPK modeling and simulating approach has several limitations. Raltegravir plasma concentrations show high variability between and within individuals due to the erratic absorption, making model development and derivation of significant covariates challenging. Various tested absorption models were not able to well describe the variable absorption with multiple peaks of raltegravir, an empirical time-varying residual error model was included.² Furthermore, we assumed that physiological changes during pregnancy had a similar effect on the 400 mg as on the 600 mg formulation. This is theoretically expected for the pregnancy effects, such as the possible increased volume of distribution and increased clearance. However, the possibly increased gastric pH, decreased gastric emptying, and increased intestinal transit time in pregnant women could impact both formulations differently.^{37,38} The 600 mg tablet is believed to disintegrate and dissolve faster as the

400 mg tablet, and a diminished influence of concomitant high-fat food intake has been observed for the 600 mg tablet.⁸ Because research indicates that the gastrointestinal changes during pregnancy have an overall minimal effect on the bio-availability of drugs,³⁹ and because the absorption of raltegravir is multifactorial and highly variable, we expect that the different gastrointestinal pregnancy effect on both formulations are likely to be negligible. The influence of physiological changes during pregnancy can also differ for the divergent food conditions and we based our conclusion on pregnancy data with moderate-fat food conditions only. We were also not able to test the effect of a moderate-fat meal on raltegravir pharmacokinetics separately, because this individual data was not available to use. We based the absence of a moderate-fat meal effect on F on earlier pharmacokinetic research.³³ Total raltegravir concentrations were predicted with our PopPK model, whereas the unbound raltegravir concentration functions as the active motion. The unbound drug fraction can change during pregnancy because the plasma protein concentration decrease.^{3,40} No data of unbound raltegravir concentration was available to us, but the difference in raltegravir unbound fraction is expected be marginal as raltegravir is modestly bound to plasma proteins (~83%).³⁵

Adequate performance of our simulations with the 1200 mg q.d. regimen is indicated by comparisons to earlier data. A historical, small, multiple-dose, pharmacokinetic study determined an GM $\text{AUC}_{0-24\text{h}}$ and C_{trough} of 26.46 mg*h/L and 0.036 mg/L in nonpregnant women in fasted state, which are similar to our predictions of 25.45 mg*h/L and 0.047 mg/L, respectively.⁸ The predicted pharmacokinetic parameters of pregnant women

using 1200 mg q.d. were also similar to the clinical data of two pregnant women from the PANNA study. The C_{trough} ratio pregnant / postpartum of these two women fell in the 90% CI of our predicted C_{trough} GMR. These subjects had an adequate virological response and no mother-to-child transition occurred.

Simulations with a PopPK model of raltegravir 1200 mg q.d. in pregnant women suggested inadequate raltegravir exposure during the third trimester of pregnancy. There is, however, a limited knowledge on the concentration-efficacy relationship of the 1200 mg q.d. regimen. Therefore, it is difficult to establish whether the inadequate exposure results in inadequate response. Although the limited, available clinical data (with lower raltegravir exposures) suggested an adequate virologic response, data of two cases are not powered to support clinical efficacy of raltegravir 1200 mg q.d. during pregnancy. A conservative approach restraining the use of the q.d. regimen in pregnant women seems reasonable until additional research confirms that ~50% lower raltegravir exposures for the raltegravir 1200 mg q.d. regimen remain effective. The raltegravir 400 mg b.i.d. regimen demonstrated adequate efficacy and safety during pregnancy and is a good alternative for these women. When treatment with raltegravir, 1200 mg is believed to be necessary in a pregnant woman, intensive viral load monitoring, and opportunistic collection of clinical and pharmacokinetic data is advised.

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CONFLICT OF INTEREST

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AUTHOR CONTRIBUTIONS

V.B., E.S., and T.P. wrote the manuscript. T.P., E.S., A.C., V.B., and D.B. designed the research. V.B., E.S., and T.P. performed the research and analyzed the data.

REFERENCES

1. DHHS. Recommendations for the use of antiretroviral drugs in pregnant women with HIV infection and interventions to reduce perinatal HIV transmission in the United States. <https://files.aidsinfo.nih.gov/contentfiles/lvguidelines/PerinatalGL.pdf>. 2020. Accessed March 3, 2020.
2. Karlsson MO, Beal SL, Sheiner LB. Three new residual error models for population PK/PD analyses. *J Pharmacokinet Biopharm*. 1995;23:651–672.
3. Anderson GD. Pregnancy-induced changes in pharmacokinetics: a mechanistic-based approach. *Clin Pharmacokinet*. 2005;44:989–1008.
4. Gilbert EM, Darin KM, Scarsi KK, McLaughlin MM. Antiretroviral pharmacokinetics in pregnant women. *Pharmacotherapy*. 2015;35:838–855.
5. Colbers A, Mirochnick M, Schalkwijk S, Penazzato M, Townsend C, Burger D. Importance of prospective studies in pregnant and breastfeeding women living with human immunodeficiency virus. *Clin Infect Dis*. 2019;69:1254–1258.
6. Cahn P, Sax PE, Squires K, et al. Raltegravir 1200 mg once daily vs 400 mg twice daily, with emtricitabine and tenofovir disoproxil fumarate, for previously untreated HIV-1 infection: week 96 results from ONCEMRK, a randomized, double-blind, noninferiority trial. *J Acquir Immune Defic Syndr*. 2018;78:589–598.
7. Cahn P, Kaplan R, Sax PE, et al. Raltegravir 1200 mg once daily versus raltegravir 400 mg twice daily, with tenofovir disoproxil fumarate and emtricitabine, for previously untreated HIV-1 infection: a randomised, double-blind, parallel-group, phase 3, non-inferiority trial. *Lancet HIV*. 2017;4:e486–e494.
8. Krishna R, Rizk ML, Larson P, Schulz V, Kesiosoglou F, Pop R. Single- and multiple-dose pharmacokinetics of once-daily formulations of raltegravir. *Clin Pharmacol Drug Dev*. 2018;7:196–206.
9. EACS. The European Guidelines for the treatment of HIV-positive adults in Europe: version 10.0. https://www.eacsociety.org/files/2019_guidelines-10.0_final.pdf, 2019. Accessed November 1, 2019.
10. Blonk MI, Colbers APH, Hidalgo-Tenorio C, et al. Raltegravir in HIV-1-infected pregnant women: pharmacokinetics, safety, and efficacy. *Clin Infect Dis*. 2015;61:809–816.
11. Watts DH, Stek A, Best BM, et al. Raltegravir pharmacokinetics during pregnancy. *J Acquir Immune Defic Syndr*. 2014;67:375–381.
12. Rizk ML, Hang Y, Luo WL, et al. Pharmacokinetics and pharmacodynamics of once-daily versus twice-daily raltegravir in treatment-naïve HIV-infected patients. *Antimicrob Agents Chemother*. 2012;56:3101–3106.
13. Eron JJ Jr, Rockstroh JK, Reynes J, et al. Raltegravir once daily or twice daily in previously untreated patients with HIV-1: a randomised, active-controlled, phase 3 non-inferiority trial. *Lancet Infect Dis*. 2011;11:907–915.
14. Blonk M, van Beek M, Colbers A, Schouwenberg B, Burger D. Pharmacokinetic drug-drug interaction study between raltegravir and atorvastatin 20 mg in healthy volunteers. *J Acquir Immune Defic Syndr*. 2015;69:44–51.
15. Blonk M, Colbers A, Poirters A, Schouwenberg B, Burger D. Effect of ginkgo biloba on the pharmacokinetics of raltegravir in healthy volunteers. *Antimicrob Agents Chemother*. 2012;56:5070–5075.
16. Van Luin M, Colbers A, Verwey-van Wissen CP, et al. The effect of raltegravir on the glucuronidation of lamotrigine. *J Clin Pharmacol*. 2009;49:1220–1227.

17. Blonk MI, Langemeijer CCA, Colbers APH, et al. Pharmacokinetic drug-drug interaction study between raltegravir and citalopram. *Antivir Ther.* 2016;21:143–152.
18. Jansen A, Colbers EPH, van der Ven AJAM, et al. Pharmacokinetics of the combination raltegravir/atazanavir in HIV-1-infected patients. *HIV Medicine.* 2013;14:449–452.
19. Krishna R, East L, Larson P, et al. Efavirenz does not meaningfully affect the single dose pharmacokinetics of 1200 mg raltegravir. *Biopharm Drug Dispos.* 2016;37:542–549.
20. Krishna R, East L, Larson P, et al. Atazanavir increases the plasma concentrations of 1200 mg raltegravir dose. *Biopharm Drug Dispos.* 2016;37:533–541.
21. Krishna R, East L, Larson P, et al. Effect of metal-cation antiacids on the pharmacokinetics of 1200 mg raltegravir. *J Pharm Pharmacol.* 2016;68:1359–1365.
22. Keizer RJ, Karlsson MO, Hooker A. Modeling and simulation workbench for NONMEM: tutorial on Pirana, PsN, and Xpose. *CPT Pharmacometrics Syst Pharmacol.* 2013;2:e50.
23. Wang L, Soon GH, Seng K-Y, et al. Pharmacokinetic modeling of plasma and intracellular concentrations of raltegravir in healthy volunteers. *Antimicrob Agents Chemother.* 2011;55:4090–4095.
24. Arab-Alameddine M, Fayet-Mello A, Lubomirov R, et al. Population pharmacokinetic analysis and pharmacogenetics of raltegravir in HIV-positive and healthy individuals. *Antimicrob Agents Chemother.* 2012;56:2959–2966.
25. Rizk ML, Du L, Bennetto-Hood C, et al. Population pharmacokinetic analysis of raltegravir pediatric formulations in HIV-infected children 4 weeks to 18 years of age. *J Clin Pharmacol.* 2015;55:748–756.
26. Lommerse J, Clarke D, Kerbusch T, et al. Maternal-neonatal raltegravir population pharmacokinetics modeling: implications for initial neonatal dosing. *CPT Pharmacometric Syst Pharmacol.* 2019;8:643–653.
27. Svensson E, van der Walt J-S, Barnes KI, et al. Integration of data from multiple sources for simultaneous modelling analysis: experience from nevirapine population pharmacokinetics. *Br J Clin Pharmacol.* 2012;74:465–476.
28. Karlsson MO, Sheiner LB. The importance of modeling interoccasion variability in population pharmacokinetic analyses. *J Pharmacokinet Biopharm.* 1993;21:735–750.
29. Petersson KJ, Hanze E, Savic RM, Karlsson MO. Semiparametric distributions with estimated shape parameters. *Pharm Res.* 2009;26:2174–2185.
30. Brainard DM, Wenning LA, Stone JA, Wagner JA, Iwamoto M. Clinical pharmacology profile of raltegravir, an HIV-1 integrase strand transfer inhibitor. *J Clin Pharmacol.* 2011;51:1376–1402.
31. Anderson BJ, Holford NH. Mechanism-based concepts of size and maturity in pharmacokinetics. *Annu Rev Pharmacol Toxicol.* 2008;48:303–332.
32. Cattaneo D, Ripamonti D, Baldelli S, Cozzi V, Conti F, Clementi E. Exposure-related effects of atazanavir on the pharmacokinetics of raltegravir in HIV-1-infected patients. *Ther Drug Monit.* 2010;32:782–786.
33. Brainard DM, Friedman EJ, Jin B, et al. Effect of low-, moderate-, and high-fat meals on raltegravir pharmacokinetics. *J Clin Pharmacol.* 2011;51:422–427.
34. Dosne AG, Bergstrand M, Harling K, Karlsson MO. Improving the estimation of parameter uncertainty distributions in nonlinear mixed effects models using sampling importance resampling. *J Pharmacokinet Pharmacodyn.* 2016;43:583–596.
35. EMA. Assessment report: Isentress. https://www.ema.europa.eu/en/documents/variation-report/isentress-h-c-860-x-0059-epar-assessment-report-extension_en.pdf 2017. Accessed March 4, 2020.
36. Bollen PDJ, de Graaff-Teulen MJA, Schalkwijk S, van Erp NP, Burger DM. Development and validation of an UPLC-MS/MS bioanalytical method for simultaneous quantification of the antiretroviral drugs dolutegravir, elvitegravir, raltegravir, nevirapine and etravirine in human plasma. *J Chromatogr B Analyt Technol Biomed Life Sci.* 2019;1105:76–84.
37. Parry E, Shields R, Turnbull AC. Transit time in the small intestine in pregnancy. *J Obstet Gynaecol Br Commonw.* 1970;77:900–901.
38. Loebstein R, Lalkin A, Koren G. Pharmacokinetic changes during pregnancy and their clinical relevance. *Clin Pharmacokinet.* 1997;33:328–343.
39. Feghali M, Venkataramanan R, Caritis S. Pharmacokinetics of drugs in pregnancy. *Semin Perinatol.* 2015;39:512–519.
40. Schalkwijk S, Greupink R, Burger D. Free drug concentrations in pregnancy: bound to measure unbound? *Br J Clin Pharmacol.* 2017;83:2595–2598.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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